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Etiology, Biology and Control of a Soilborne Root Rot Complex of Green Peas

J. C. Tu

Agriculture Canada, Research Branch, Research Station, Harrow, Ontario NOR 1GO

ABSTRACT

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The field incidence of pea root rot in southwestern Ontario averaged 26%. The root rot complex has severely curtailed green pea yield. In order to resolve the etiology of this complex, a total of 782 fungal isolations were obtained from 465 samples collected from 33 pea fields. The isolations yielded *Fusarium solani* f. sp. *pisi, F. oxysporum* f. sp. *pisi, Aphanomyces euteiches* and *Pythium* spp. in 7:4:1:1 frequency. The ratio of races 1 and 2 in the *F. oxysporum* isolates was 7:4. *F. solani* did not appear to be highly specialized and no attempt was made to determine its race profile. The disease severity caused by *F. solani* (root rot), *F. oxysporum* (wilt), *Pythium* and *Aphanomyces* averaged 3.2, 8.7, 2.6 and 4.0, respectively, on a 0-9 scale. Plants with Fusarium wilt usually died while those with Fusarium root rot showed various degrees of stunting and yellowing but rarely died. *Pythium* and *Aphanomyces* are considered to be minor problems in Ontario. Based on this information, a disease damage index (DDI) was developed to rank the relative importance of these four root rots. The DDI of a root rot equals the total amount of root rot (26.5%) × the frequency of occurrence of each fungus × the severity of disease caused by each fungus. The DDIs for *F. solani, F. oxysporum, Pythium* spp. and *A. euteiches,* were 45, 71, 5 and 8, respectively. Therefore, Fusarium wilt is the most damaging disease followed by Fusarium root rot. While *Pythium* and *Aphanomyces* root rot are of minor importance. Based on the etiological and biological findings, an integrated control program has been developed. The program includes: (a) development of a new seed treatment formulation; (b) trial and selection of disease resistant cultivars; (c) formulation of suitable herbicide combinations; (d) development of a soil indexing procedure; (e) improvement of tillage practices; (f) adoption of interseason green manure crops and (g) modification of soil pH. The success of this integrated disease control program has brought pea root rot under control and increased pea yield by 150% over a three-year (1984 to 1986) period.

INTRODUCTION

Approximately 9,000 ha of green peas were planted each year[5]. A survey of 550 ha showed that root rot disease affected about 26% of the plant population. Many fields sustained total loss. Average pea yields in Ontario in 1983 were only 1.5 t/ha, where a yield of 5.0 t/ha is possible if root rots are brought under control[6].

The etiology of pea root rots in southwestern Ontario has not been fully resolved. There are more than 20 different fungi that can cause pea root rot[3]. Root rot disease of peas in different regions of the world may be caused by different fungi as a reslut of geographical and environmental differences. In Canada the most frequently isolated root rot fungi of peas have been *Fusarium solani* (Mart., Appel & Wr.) f. sp. *pisi* (F. R. Jones, Snyd. & Hans.), *F. oxysporum* (Schlect.) f. sp. *pisi* (Snyd. & Hans.) and *Pythium* spp., with *Asochyta pinodella* L. K. Jones and *Rhizoctonia solani* Kuhn isolated occasionally[7,20]. *F. solani* has been reported to be the predominant root rot fungus in southern Ontario[7], unfortunately, these reports have been based upon limited surveys. The frequency of isolation of specific pathogens has not been reported, nor the relative severity of disease caused by different root rot fungi. No recent systematic research efforts have been attempted on pea root rot in Ontario, so that new information is needed to develop an integrated control program (ICP) for the Ontario pea root rot complex. A detailed survey and controlled experiments are required to obtain information with respect to etiology, and biology of this disease complex.

This paper discusses the application of a quantitative approach toward etiological determination and application of biological findings in the development of integrated disease control measures.

MATERIALS AND METHODS

Etiology

A survey was conducted in Essex and Kent counties in southwestern Ontario. Totals of 600 and 800 ha were surveyed in 1983 and 1984, respectively. The acreages represented 50 and 75% of the total acreage of the largest pea processing company in the area. Since peas were grown exclusively for the company on contracts, the growers' fields to be surveyed were selected randomly from lists provided by the company.

Surveys were conducted between late May and mid-June each year. For each field, four replications of 10 plants were dug up and the incidence and severity of root rots were assessed. The severity was determined using a 0 to 4 scale in which 0 = healthy, 1 = 0-10%, 2 = 11-25%, 3 = 26-50% and 4 = 51-100% of the root discolored.

A large scale isolation was conducted in 1983 in conjunction with the disease survey. A total of 465 samples was collected randomly from 33 pea fields. Isolations were made by cutting small pieces (ca., 1 mm^3) of discolored root tissue. The tissue pieces were surface sterilized in 1.65% sodium hypochloride solution for 1 min, rinsed in distilled water and placed on an agar plate containing potato dextrose agar (PDA) and 40 μg /mL of novobiocin. For each petri plate, 4 pieces of tissue were plated. The plates were incubated at 22℃. After a 4-day incubation, the fungi that grew out of the tissue pieces were isolated and later identified on the basis of pathogenicity to a series of differential pea cultivars[16].

Development of a new seed treatment formulation

The etiology of this disease complex has been resolved and is reported later in the results section. Frequencies of isolation of *F. solani, F. oxysporum, Aphanomyces euteiches* and *Pythium* spp., were 7:4:1:1. It becomes apparent that *Pythium* and *Aphanomyces* are not a major component of this disease complex and should be controlled by seed treatment. Unfortunately, captan is the only chemical routinely used in treating pea seeds. Since captan cannot control Phycomycetous fungi, such as *Pythium* and *Aphanomyces*[23] other chemicals should be sought.

Several fungicides were assayed in the laboratory against *Pythium ultimum* and *Aphanomyces euteiches.* They were: benalaxyl, Dowco-444, metalaxyl, Ortho-Xe779, propamocarb, Re 26745 and oxadixyl. Two concentrations of fungicides were used, 40 μg a.i. /mL and 100 μg a.i./mL (Fig. 1). The fungicides were mixed into potato dextrose agar (PDA) which was plated in 10-cm petri plates. Small mycelial discs, 5 mm in diameter were punched from the actively growing colonies of *P. ultimum* and *A. Reuteiches* on PDA and transferred to the fungicide containing PDA, one disc per plate. For each fungus-chemical-dosage combination 4 replicated plates were prepared. The diameter of the colony was measured daily for one week. The experiment was repeated.

Seeds of the cultivar GG313, a wrinkle-seeded pea, were used throughout the test. Three fungicide dosages were used (i.e. 15, 30 and 60 g a.i./100 kg of seeds). The seeds and the fungicide were poured into a seed tumbler and a small amount of water was added. The seeds were tumbled for several minutes until they were evenly coated with the fungicide. Treated seeds were planted in potted soil obtained from a field with heavy root rot infestation, 100 seeds/25 cm pot at a depth of 2 cm below the soil surface. Four pots were planted for each dosage-chemical combination. After sowing, the pots were kept in a greenhouse at 21 ± 2℃ and watered as required. Germination counts and root rot ratings were made 2 and 4 weeks after sowing, respectively. Root rot severity was determined on a 0-9 scale, in which 0 = less than 10% of root with symptoms, 1 = 10-20% of root with symptoms, etc., 9 = plant dead. This rating system (0-9 scale) was also used in all experiments unless otherwise stated.

Based on the above evaluations, chemicals that were effective against *Pythium* and/ or *Aphanomyces* and had no apparent phytotoxicity were selected. Metalaxyl and oxadixyl were selected for *Pythium* and Dowco-444 and benalaxyl for *Aphanomyces.* Three new formulations were developed in combination with captan. They were (a) captan, benalaxyl and metalaxyl; (b) captan, Dowco-444 and oxadixyl, and (c) captan, Dowco-444 and metalaxyl. To test their efficacy, each chemical was applied at three dosage levels (15, 30 and 60 g a.i./100 seeds). The treated seeds were planted in the same manner as described previously in the seed germination tests. Germination and root rot severity were determined as described above.

Trial and selection of resistant cultivars and lines

Most cultivars used in Ontario are highly susceptible to Fusarium wilt and root rot. An evaluation of a range of commercial cultivars and breeding lines for resistance to the Ontario root rot complex was conducted including cultivar trials, testing for specific resistance to Fusarium wilt and for non-specific resistance to Fusarium root rot. Although some pathotypes of *F. solani* have been reported[8], it is felt that the species is not yet

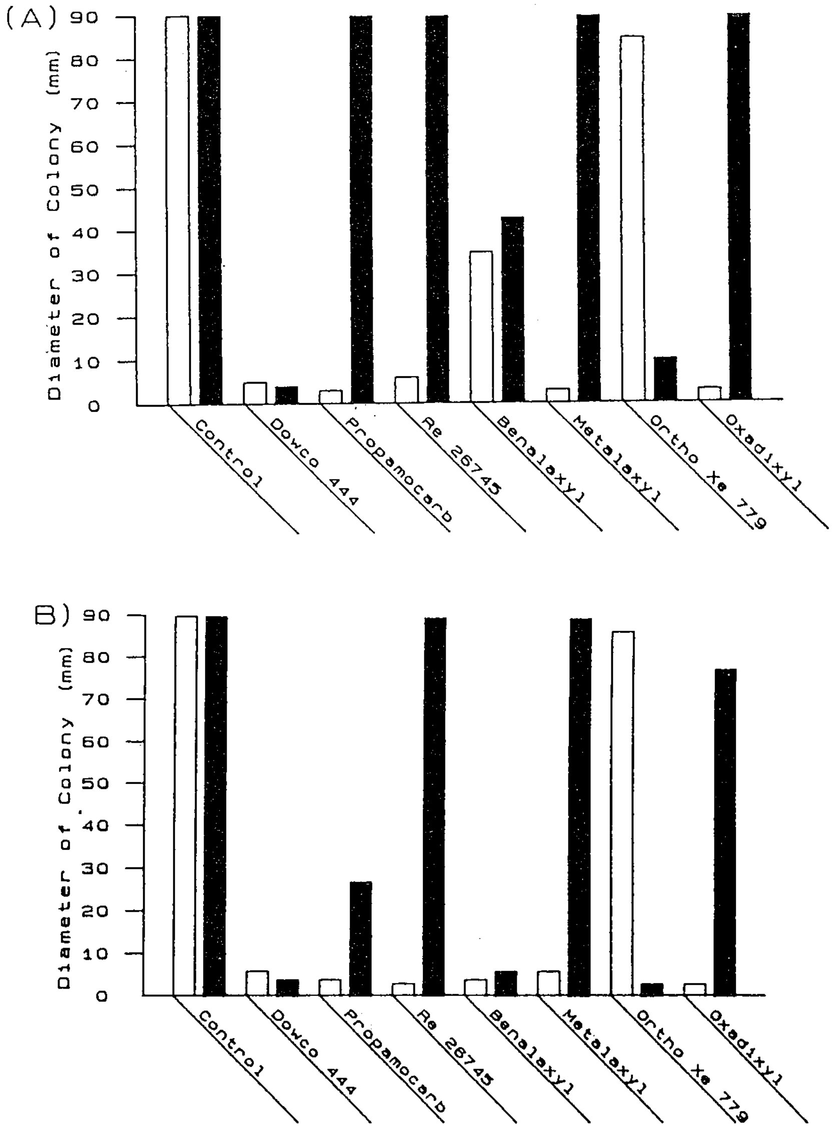

Fig 1. Effect of various fungicides on growth of *Pythium ultimum* (white bar) and *Aphanomyces euteiches* (black bar). Two concentrations of fungicides were used, 40μg a.i./mL (A) and 100 μg a.i./mL (B).

highly specialized.

Cultivars of peas were obtained from various research organizations and seed companies between 1983 and 1986. Each year, between 150 and 200 cultivars and lines were tested in 4 replications of randomized single rows in a field with severe root rot infestations. The ratio of Fusarium wilt and Fusarium root rot was approximately 7:4.

Root rot severity was rated on a 0-9 scale in the last week of June, with 20 plants examined in each row. Cultivars and breed-

ing lines which had a disease severity rating of 0 to 4 should have a high to moderate resistance to the disease complex of Fusarium wilt and root rot.

Formulation of suitable herbicide combinations

MCPB, MCPA and MCPA/MCPB (1:15), phenoxy compounds, are the most commonly used post-emergent herbicides for peas in Ontario. These herbicides have been found to increase root rot severity and exacerbate symptom expression[27]. Twelve herbicide treatments consisting of different combinations, rates and methods of application (see Table 9) were evaluated over a 3-year period. A moderately infested field in which a standard susceptible cultivar, (GG 512), usually showed in 100% infection with a disease severity rating of approximately 5.0 in a 0-9 scale was used. Herbicides were applied in accordance with the manufacturers' recommendations. Preplant incorporation were applied immediately before sowing, post-emergent spraying was applied about 4 weeks after sowing. Peas were sown each year in the first week of May. The 12 herbicide treatments and a control were randomized in each of 4 replicate blocks. A treatment plot consisted of 20 rows, 7 m long and 20 cm apart with 40 seeds/m. Root rot were rated on or about June 24 as weather permitted. In each test plot, 40 plants were scored on a 0-9 scale.

Development of a soil indexing procedure

F. oxysporum and *F. solani* are soil inhabitants. Incidence and severity of root rots are related to the density of inoculum in the soil, and fields with a previous history of root rot are likely to have an ongoing problem when susceptible cultivars are planted. Sherwood and Hagedorn[21] have developed a soil indexing method for common root rot (*A. euteiches*) of peas. This method was adapted to estimate the inoculum density of the predominantly *F. solani* and *F. oxysporum* in Ontario fields. However, the method proved to be laborious and costly. As an alternative, an on-site testing program was developed to evaluate the recommended cultivars in a small area of growers' fields one year prior to commercial production.

Improvement in tillage practices

Soil compaction increases incidence and severity of root rots[12,28]. Therefore, the effect of various tillage practices was investigated.

The field experiments were conducted on Brookston clay, a fine textured soil classed as an Orthic Humic Gleysol. This soil type, one of the most widely distributed in southwestern Ontario, has shown favorable response in yield when soil compaction is reduced[9].

A Latin square design was used to compare five tillage treatments planted in a east-west direction with green manure treatments superimposed running north-south.

The experiments were conducted in a field previously showed 100% disease incidence and an average disease severity of 8-9 on a 0-9 scale.

The five tillage practices applied were:

(1) Fall plough + spring flat seed bed preparation (FP);
(2) Fall plough + spring flat seed bed preparation + compaction (FPC);
(3) Fall plough + fall flat seed bed preparation (FP-FSBP);
(4) Fall chisel plough + spring flat seed bed preparation (CP);
(5) Fall plough + spring raised seed bed (20-cm in height) preparation (FPB).

The fall tillage practices were carried out in late October, and the plots left until mid-

April of the following year. Spring seed bed preparation involved smoothing the land with a triple-K. Soil compaction was achieved by running tractor wheels over the plots. Compacted and non-compacted fields had penetrometer readings of 11.0 and 18.0 kg pressure at 18 cm depth respectively using a Bush Recording Soil Penetrometer (Findlay & Irvine Ltd., Midlothian, Scotland).

Peas (cv. GG512) were planted each year in the first week of May. Pea root rot ratings were recorded in the third week of June. For each rating, 4 replications of 10 plants per plot were examined. The experiments were continued for 3 years (1984-86). The weight of pea plants were recorded at the same time.

Adoption of interseason green manure crops

The root rot disease complex that causes severe loss in this area can be attributed to long term improper cultural practices. One potentially beneficial practice is the growing of interseason green manure crops. At present, this is not widely practiced. The impact of interseason green manure crops in pea root rot disease control was investigated along with tillage practices using a Latin square design.

Bean, peas, rye, oats, corn, sudan grass and sorghum were grown as interseason green manure crops in two root rot-infested fields (one heavily and the other moderately infested). Immediately following the pea harvest in mid-July, the fields were chisel ploughed, disced, smoothed and sown to green manure crops. Cultivars of green manure crops, seeding rates and row width are listed in Table 1. At the end of October, samples were taken from each crop to estimate the amount of green manure production. Later, the green manure crops were chopped and incorporated into the soil.

In early May of each year, a root rot susceptible cultivar of pea (cv. Green Giant 512) was planted in 15 cm rows in both heavily infested and moderately infested fields. A randomized block design was used. There were four replications of each test. Root rot severity and pea growth were determined in the third week of June and first week of July, respectively, using a 0-9 scale. For pea growth, plants were sampled for fresh weight determination. For each plot four replications of 10 plants were sampled.

Effect of soil pH on root rots

i) *Effect of liming on plant growth, root rot severity and pea yield in a green manured and non-green manured soil*

A split plot design with 4 replicates was employed to compare green manured and non-green manured soil relative to quantity

Table 1. Cultivar and seeding rate of various green manure crops

Crop	Cultivar	Row width (cm)	Seeding rate (kg/ha)
Pea	Green Giant 512	15	246
Bean	Improved Tender Green	60	90
Rye	Empire	15	108
Sorghum	Silo Maker	15	81
Oats	Garry	15	100
Corn	Pioneer 3707	60	22
Sudan grass	Trudan 8	15	81

of liming. After the pea harvest in early July, one half (24 × 10 m) of each plot (approx. 24 × 20 m) was planted with field corn (cv. Pioneer 3707) at 60 cm row width and 22 kg/ha seeding rate and the other half left bare. In mid October, 1986, the corn plants were chopped. The yeild of green manure was estimated to be 8.8 t/ha. Immediately after, the plot was strip (3 m wide) limed by spreading dolomitic lime at a rate of 0, 0.5, 1.0, 2.0, 3.0, and 4.0 tonnes per ha and then disced to thoroughly incorporate the lime and green manure into the soil. The plot was left over the winter and planted with pea (cv. G.G. 512) in the first week of May, 1987. Fresh weight of plants, root rot severity, green pea yield and soil pH readings were recorded in the third week of June.

ii) *Effect of liming on soil microbial activity in a green manured and non-green manured soil*

In early July, soil samples were taken in four replications from the top 10 cm of soil with a core sampler. A series of dilutions (10^{-1} to 10^{-6}) were prepared from each soil sample. For bacterial count, 0.01 of a dilution was applied to a PDA plate. The plates were incubated at 22 ℃ and colonies were counted 48 h later. For fungal count, 0.01 of a dilution was applied to a PDA plate containing 40 μg/mL of tetracycline. The plates were incubated at 22 ℃ and fungal colonies were counted 72 h later. Root rot fungi were visually differentiated from other saprophytic fungi recognizing that a margin of error exists with this method of determination. Each dilution was plated four times.

iii) *Effect of different green manure on soil microbial activity*

Soil that was heavily infested with pea root rot fungi was brought into the greenhouse from the field in Tecumseh. The soil was limed with dolomitic lime to bring its pH to 6.5, an optimal pH for microbial activity determined in previous experiments[25]. The soil was divided into eight subsamples. One subsample was reserved as an untreated control and the other seven were allotted to seven different green manures (i.e. pea, bean, rye, sorghum, oats, corn and sudan grass). The green manures were harvested from the filed, oven derived at 55 ℃ and ground in a Mill grinder with a 2 mm^2 screen.

Two percent by weight of each type of ground dried green manure was added to each soil preparation, throughly mixed in a cement mixer and placed in 13 cm-pots. No dried green manure powder was added to the control. Each treatment consisted of eight replicated pots. The pots were kept constantly moist in a greenhouse at 22 ± 2 ℃ for a six month digestion. Later, the pots were divided into two groups. One was planted with peas (cv. G.G. 512) to assess the severity of root rots and the other was used for soil sampling to determine the soil microbial population using a method described previously. Root rot severity of pea was scored two months after sowing.

RESULTS AND DISCUSSION

Etiology

Root rot survey. The incidence of pea root rot varied widely from field to field and differed greatly from one cultivar to the other. Variation among fields ranged from 0 to 98.5% and cultivars from 15.8 to 53.5% (Table 2). Similarly, the disease severity also varied widely among cultivars. For example, GG451 had an average root rot severity rating of 1.6 versus a 3.3 rating for GG 313 on a 0 to 4 scale (Table 2). The differences in incidence and severity among pea cultivars indicate that some cultivars may be more tol-

erant to one or more root rot pathogens.

Isolation of root rot organisms. Isolations were prepared from 465 samples collected from 33 pea fields, from which 782 fungal cultures were isolated. Of the 782 fungal cultures, 356 were *Fusarium solani,* 201 were *F. oxysporum,* 58 were *Aphanomyces euteiches,* 48 were *Pythium* spp. (mostly *P. ultimum*), 6 *Rhizoctonia solani,* 5 *Thielaviopsis basicola* and the remainder (108) were non-pathogenic fungi, mostly common soil inhabitants. Frequencies of isolation of *F. solani, F. oxysporum, Aphanomyces euteiches* Drechs and *Pytium* spp. were 7:4:1:1[24]. Other fungi, e.g., *R. solani, A. pinodella* and *Thielaviopsis basicola* (Berk. & Br.) Ferraris, were isolated only occasionally.

Overall disease severity and yield loss are the sum of the effects of each component fungus. The incidence of pea root rot in southern Ontario averaged 26.5%. Disease severity of each root rot was determined on a scale of 0 to 9. The severity of disease caused by *F. solani* (root rot), *F. xysporum* (wilt), *Pythium* and *Aphanomyces* averaged 3.2, 8.7, 2.6, and 40, respectively. Isolates of *F. oxysporum* were identified as races 1 and 2 by a differential scheme[12] and known races provided by J. M. Kraft of Prosser, Washington. The ratio of race 1 to race 2 was 7:4.

Table 2. Incidence and severity of pea root rot in 1983 and 1984 in Essex and Kent counties

Cultivar	Area (ha)						Root rot			
	Total		Surveyed		% Surveyed		Incidence (%)		Severity[1)]	
	1983	1984	1983	1984	1983	1984	1983	1984	1983	1984
E.J. 235	92.7	90.9	45.9	67.7	50.0	73.6	53.5	34.1	2.1	2.7
Sparkle	131.8	66.4	80.5	48.2	60.6	72.7	15.8	21.1	3.2	2.8
Mini 381	207.7	135.0	111.4	99.5	53.6	74.1	21.3	22.8	2.0	2.1
G.G. 313	188.2	–[2)]	74.5	–	39.9	–	43.3	–	3.3	–
G.G. 451	10.0	422.0	0.0	320.0	0.0	75.8	NA	20.2	NA	1.6
G.G. 512	387.3	307.0	222.3	248.2	57.3	80.8	20.7	21.1	2.2	1.8

1) Root rot rating based on a scale of 0-4 in which 0 = healty, 1 = 0-10%, 2 = 11-25%, 3 = 26-50% and 4 = 51-100% of the root discolored.
2) Cultivar discontinued in 1984.

On the basis of this information, and assuming that hosts, environmental conditions, and cultural practices are random relative to isolation, a simple disease damage index (DDI) can be developed to rank the root rot fungi according to etiologic importance. The DDI of a root rot equals the total amount of root rot × the frequency of occurrence of each root rot fungus × the severity of disease caused by each fungus. The DDIs (Table 3) show that Fusarium wilt is the most serious problem, followed by Fusarium root rot. Plants with Fusarium wilt usually die, whereas plants with Fusarium root rot show various degrees of stunting and yellowing and droopy in warm, sunny afternoons, but rarely die. *Pythium* and *Aphanomyces* root rots are minor problems in Ontario.

Development of a new seed treatment formulation

Bioassay of various fungicides against *P. ultimum* (Pu) and *A. euteiches* (Ae) showed

Table 3. Disease damage index (DDI) of each fungus in the Ontario root rot complex (average incidence = 26.5%)

Fungus	F.O.[1)]	D.S.[2)]	DDI
Fusarium solani	7/13	3.2	45
F. oxysporum	4/13	8.7	71
Pythium spp.	1/13	2.6	5
Aphanomyces euteiches	1/13	40.0	8

1) Frequency of occurrence.

2) Disease severity, based on a 0-9 scale, in which 0 = <10% of root with symptoms, 1 = 10-20% of root with symptoms, 9 = plant dead.

that Pu was sensitive to Dowco-444, propamocarb, RE 26745, metalaxyl, oxadixyl and benalaxyl (Fig. 1). Ae, however, was sensitive only to Dowco-444, RE 26745, Ortho-Xe 779 and benalaxyl (Fig. 1).

Although Pu and Ae are both phycomycetous fungi, they differ in their sensitivity to chemicals. Of the above chemicals Dowco-444, RE 26745 and Ortho-XE 779 are still in the experimental stage of development and the availability of propamocarb is limited. In addition, Ortho-XE 779 had an adverse affect on seed germination (Table 4). Therefore, benalaxyl and metalaxyl were chosen for Ae and Pu, respectively.

All above fungicides had some residual effect in controlling root rot as compared with untreated control (Table 5). The residual effect was more apparent for Ortho-XE 779, propamocarb, oxadixyl and RE 26745 than metalaxyl and captan (Table 5).

It must be pointed out that the high root rot indices were expected, because the residual effects of seed treatment fungicides were limited. GG 313 is a highly susceptible cultivar to root rot and they were grown in a soil with high inoculum density.

Three new formulations were developed and evaluated. These were: (a) captan-benalaxyl-metalaxyl, (b) captan-Dowco-444-oxadixyl and (c) captan-Dowco-444-metalaxyl Seeds treated with any of the 3 formulations gave significantly higher percentage of germination and somewhat lower root rot severity than untreated control (Table 6).

These results suggest that addition of fungicide specific to phycomycetous fungi to captan for seed treatments is desirable. Seed

Table 4. Effect of fungicides on seed germination

	% germination of treated seed[1)]							
g fungicide per 100 kg seed	Control untreated	Captan	Xe-779	Oxadixyl	Propamocarb	Metalaxyl	Re 26745	Dowco-444
15	64.0	73.0 a	43.3 a	81.0 a	82.5 a	69.3 a	81.0 a	78.5 a
30	64.0	70.5 a	35.3 b	77.5 ab	76.5 b	73.5 a	78.0 a	70.5 b
60	64.0	71.3 a	28.3 c	75.3 b	71.3 c	77.8 a	78.5 a	74.5 ab

1) Means within columns followed by the same letter are not significantly different (P > 0.05) according to Duncan's multiple range test.

Table 5. Root rot severity in 4 week-old plants grown from seeds treated with different fungicides (60 g a.i./100 kg seed for each chemical)

Fungicide	Severity of root rot (0-9 scale)[1]
Control (not treated)	8.8 a[2]
Captan	7.6 b
Ortho Xe-779	7.7 b
Propamocarb	6.4 c
Metalaxyl	7.2 bc
Dowco-444	6.4 c
Oxadixyl	6.4 c
Re 26745	6.4 c

1) See footnote of Table 3.
2) See footnote of Table 4.

Table 6. Comparison of the 3 new seed treatment formulations on seed germination and root rot severity on 4-week-old plants.

g fungicide of each component per 100 kg seeds		Captan benalaxyl metalaxyl	Captan Dowco-444 oxadixyl	Captan Dowco-444 metalaxyl
15	Seed	77.5 a[2]	80.0 b	71.8 a
30	germination	81.0 b	74.5 a	84.0 c
60	(%)	78.8 a	83.8 c	82.0 b
15	Root rot	8.2 c	8.5 c	8.5 c
30	severity	7.8 b	8.0 b	8.1 b
60	(0-9 scale)[1]	7.1 a	7.3 a	7.5 a

1) See footnote of Table 3.
2) see footnote of Table 4.

treatment with the new formulations increased seedling stand by an average of 24 to 31% and 13 to 18% over untreated control and captan treated seeds. Seed treatment alone cannot control root rots of peas, but it may form a component of an integrated control program.

Trial and selection of disease resistant cultivars

The results (Tables 7 and 8) showed that many commercial cultivars and breeding lines had a disease severity rating of 0 to 4. These results indicated that these cultivars and lines had a high to moderate resistance to the disease complex of Fusarium wilt and root rot in Ontario.

These resistant cultivars (Table 7) could be adopted readily into commercial production in southwestern Ontario. Many of the resistant breeding lines (Table 8) could be developed into new cultivars or used in breeding for disease resistance.

All cultivars and breeding lines which had a rating of 4.1 to 9.0 were moderate to

Table 7. Response of cultivars to the disease complex of Fusarium wilt and root rot of peas in southwestern Ontario[1)]

Root rot severity Index (0-9 scale)[2)]	Cultivar[3)]				
0-1.0	Perfection WR[1]				
1.1-2.0	Early Perfection[2]	RS-7[3,4]	Parlay[2]	Green Giant 531 (Nuttall selection)[1]	
2.1-3.0	New Season[2]	Anoka[2]	Novella[2]	Almotto[2,4]	Puget[2]
	Bolero[5,6]	Medalist[6]	M140[2]	Early Perfection 3040[2,4]	
	Home Guard[1]				
3.1-4.0	Frontier[7]	Parlay[8]	Alaska 423[9]	Early Forsty[2]	Mini[2]
	Maro[2]	Little Sweetie[11]	Massette[10]	Jade[2]	M-129[1]
	Olympia[12]	Mercurio[10]			

1) This list may include some private cultivars and named breeding lines. Interested parties who wish to obtain seeds should write directly to their respective sources.
2) For 0-9 scale, see footnote of Table 3. Cultivars having a rating higher than 4 are not listed.
3) The superscripts following each cultivar indicate the suppliers of seeds: 1: Mr. V. W. Nuttall (deceased), Harrow Resarch Station, Ontario; 2: Dr. R. J. Howard, Alberta Horticultural Research Center, Brooks, Alberta; 3: Dr. T. P. Reiling, Pilllsbury Co. Le Sueur, Minn.; 4: Dr. J. M. Kraft, Irrigated Agriculture Research and Extension Center, WN.; 5: Libby Co., Ontario; 6: Asgrow Seed Co., MI; 7: Canadian Canners Ltd., Ontario; 8: Roger Bros. Seed Co., Ontario; 9: Dr. A. A. Reyes, Vineland Research Station, Ontario; 10: Del Monte, California; 11: Stokes Seeds Ltd., Ontario; 12: Harris Moran Co. Seed, Ontario.

highly susceptible and were excluded from the tables.

Formulation of suitable herbicide combinations

Some herbicides increased, some had no effect and some reduced the severity of pea root rot (Table 9). Herbicides that reduced root rot were: (a) pendimethalin, (b) cyanazine, (c) pendimethalin + cyanazine, (d) trifluralin + cyanazine and (e) oryzalin + trifluralin. These are all dinitroaniling compounds except the triazine, cyanazine. In the triazine group, prometryne appears to be neutral with respect to root rot severity. Benzoic acid (chloramben) and phenoxy compounds (MCPA and MCPB) generally increased the severity of root rot in peas.

Dinitroaniline and dinitramine herbicides that reduce root rots caused by phycomycetous fungi[(2,10,15)] have been shown to disrupt the flagella of zoospores[(22)]. Since most fields in Ontario have a very highdensity of *Fusarium* spp. and a negligible amount of *Pythium* spp.[(20)], the reduction in severity of pea root rot by these treatments may be attributable to some other factor.

The phenoxy compounds (MCPA, MCPB and MCPA/MCPB) are somewhat similar in structure and function to 2,4-D and are plant growth regulators[(4)], while the dinitroaniline and dinitramine herbicides are inhibitors of protein synthesis and tend to reduce root elongation[(4)].

Development of a soil indexing procedure

Table 8. Response of breeding lines to the disease complex of Fusarium wilt and root rot of peas in southwestern Ontario.[1]

Root rot Severity Index (0-9 scale)[2]	Line[3]				
1.1-2.0	9602-10 a	97067-1-5-1 a			
2.1-3.0	80-717 cd	7710-4-1-2 a	9731-3 a	X9602-7 a	494-All bc
	7801-10-3 a	X9500-1-1 a	9601-3-7-2 a	9816-14 a	8221-5a
	9601-3-3 a	C82-409 e	9713-6-1 a	9713-30 a	7601-2-1-4 a
	X9725-8 a	X9504-2-3 a	74-SN5 b	WSU R22 bc	
	Minnesota 108 bcd				
3.1-4.0	7705-7 a	X9727-10 a	X9602-2 a	VR1492-1 bc	508-7a
	9603-10-12 a	89617-EP a	83-1356 f	7712-10 a	P.I.189171 bc
	9406-1 a	9728-8 a	83-1392 f	7025a	WR1158 f
	X9726-2 a	89171 b	9889-2 a	9888a	PH14-119 b
	7705-8 a	507-8 a	9716-1-1 a	OH69.22 g	8615-3EP a
	74-SN4 bc				

1) The list may include some numbered cultivars and private breeding lines. Interested parties who wish to obtain seeds should write directly to their respective sources.
2) For 0-9 scale, see footnote of Table 3. Lines having a rating higher than 4 are not listed.
3) The superscripts following each line indicates the suppliers of seeds: a: Dr. D. Polson, Canners Seed Co., Idaho; b: Dr. R. J. Howard, Horticultural Research Station, Alberta; c: Dr. J. M. Kraft, Irrigated Agriculture Research and Extension Center, WN.; d: Pillsbury Co. Le Sueur, Minn.; e: Roger Bros. Seed Co., Ontario; f: U.S.D.A., Beltsville, Md.; g: Mr. V. W. Nuttall (deceased), Harrow Research Station, Ontario.

Table 9. Effect of different herbicides on the severity of root rot of peas grown in soil with moderate fungal infestation

Treatment	Rate (kg/ha)	Application	Root rot severity (0-9 scale)[2]
Control			5.2 b[3]
chloramben	3.0	Pre[1]	6.1 c
cyanazine	2.0	Pre	4.4 a
pendimethalin + cyanazine	2.0	Pre	4.4 a
prometryne	2.2	Pre	5.1 b
trifluralin; MCPA	0.8; 0.4	Ppi; Post	5.9 c
trifluralin; MCPB (Tropotox)	0.8; 1.7	Ppi; Post	7.3 d
trifluralin; MCPB (Thistrol)	0.8; 1.7	Ppi; Post	7.4 d
trifluralin; MCPA/MCPB	0.8; 1.7	Ppi; Post	7.6 d
oryzalin	0.8	Ppi; Post	6.2 c
pendimethalin	2.0	Ppi	4.3 a
trifluralin + cyanazine	0.8 + 1.5	Ppi	4.0 a
oryzalin + trifluralin	0.4 + 0.4	Ppi	4.3 a

1) Per = pre-emergent spray, Ppi-preplant incorporation and Post = post emergent spray.
2) A three-year average. For 0-9 scale, seed footnote of Table 3.
3) See footnote of Table 4.

Soil indexing conducted in pots in the greenhouse and in short rows in the field was equally effective. In fact, the variation in disease severity was smaller in the field than in the greenhouse. In-field soil indexing allowed the testing of more cultivars, so that in-field soil indexing was preferred in practical farming operations.

Improvement in tillage praction

Tillage practices played an important role in root rot severity in root rot infested fields. The results of 1985 and 1986 were generally similar and only 1986 data are presented (Table 10).

Most of the variation among the tillage practices could be associated with the comparison of treatments 1, 2 and 3 with treatments 4 and 5. FPB and CP had lower incidence of root rot and FPC gave the highest root rot severity.

Adoption of interseason green manure crops

Effect of green manure on root rot — The results (Table 11) showed that even one interseason of green manure incorporation in the fall of 1983 effectively reduced the severi-

Table 10. Effect of different tillage practices on severity of pea root rot in fields with heavy root rot infestation.

Tillage practice	Root rot severity (0-9)[1]	Fresh wt of plants (g) (40 plants)
1. Fall ploughing + spring seedbed (FP)	7.7 b[2]	78.6 c
2. Fall ploughing + compaction (FPC)	8.0 bc	29.6 e
3. Fall ploughing + fall seedbed (FP-FSBP)	7.5 b	58.4 d
4. Chisel ploughing + spring seedbed (CP)	7.0 ab	88.4 b
5. Fall ploughing, raised beds (FPB)	6.4 a	115.4 a

1) For 0-9 scale, see footnote of Table 3.
2) See footnote of Table 4.

Table 11. Effect of 1, 2 and 3 years of interseason green manure crops on root rot severity of peas in fields with heavy root rot infestation.

Green Manure Crop	Root rot severity (0-9)[1]		
	1984	1985	1986
Control (none)	7.0 b[2]	7.3 c	7.8 c
Peas	8.8 c	8.6 d	8.7 d
Beans	7.3 b	7.4 c	8.2 d
Rye	7.0 b	6.8 bc	7.4 c
Oats	6.2 a	5.8 a	5.5 a
Sorghum	6.0 a	6.5 b	5.6 a
Corn	6.8 b	6.5 b	6.4 b
Sudan grass	6.8 b	6.3 b	6.4 b

1) For 0-9 scale, see footnote of Table 3.
2) See footnote of Table 4.

ty of the root rot disease in the subsequent pea crop in 1984. Of the seven green manure crops employed, peas and beans resulted in a slight increase in disease severity, particularly peas. Rye had little or no effect but the other graminaceous species (oats, corn and sudan grass and sorghum) reduced root rot severity significantly, with oats the most effective.

When the same green manure procedure was repeated for the 2nd and 3rd years in heavily infested fields, pea root rot severity in plots with oats, corn, sudan grass and sorghum as green manure showed a gradual but steady decline over the years. In contrast, plots with beans, peas and rye as green manure showed either a slight increase or remained unchanged. The pea root rot severity in control plots also increased slightly.

Effect of soil pH on root rots. A field survey showed that there were no significant differences in root rot severity relative to soil pH; however yield was related to soil pH. The most favorable soil pH for pea yield was between pH 5.9 and 6.4. Acceptable yields were obtained between pH 5.4 and 5.9 and pH 6.4 and 7.0 while pH values below 5.4 were unfavorable (Table 12).

i) *Effect of liming on plant growth, root rot severity and pea yield in a green manured and non-green manured soil in the field*

Liming a heavily root rot infested field with various amounts of dolomitic lime resulted in increase of soil pH from an unlimed check of pH 5.5 to a maximum of pH 7.2. Plant growth and yield on green-manured and non-manured soils responded differently to soil pH. The greatest plant growth and green pea yield were found between pH 5.9 and 6.5 in non-green manured soil and pH 6.5 and 7.0 in green manured soil. Increase and decrease in soil pH from the optimal ranges resulted in a gradual decrease in plant growth and pea yield (Table 13). Root rot severity responded to liming somewhat similarly to plant growth and pea yield, but the ranges were considerably smaller (Table 13). An apparent synergistic interaction existed between green manuring and liming. For example, at optimal soil pH (6.5), plant growth and pea yield in green manured soil increased approximately 30 to 40% over the non-green manured soil. The favorable pH range for plant growth in green manured soil was broader (pH 6.5-7.2) than those (pH 5.9-6.5) in non-green manured soil (Table 13).

ii) *Effect of liming on soil microbial activity in a green manured and non-green manured soil in the field*

Although the soil pH increased as lime was added to the soil, the increases in soil pH were not proportional to the amount of lime added (Tables 12 and 13). There was a significant interaction between green manuring and liming in terms of microbial population in the soils.

Table 12. Relationship between soil pH and severity of root rot

pH	<5.0	5.0-5.4	5.5-5.9	6.0-6.4	6.5-6.9	7.0
No. of field	1	11	26	12	9	4
Ave. pH	4.85	5.30	5.74	6.28	6.75	7.11
Ave. root rot (0-4 scale)	0.9 a[1)]	2.0 b	1.8 b	19 b	2.3 b	2.5 b
Ave. yield of pea (kg/ha)	2,344 a	2,976 b	3,327 c	4,083 d	3,092 b	3,186 b

1) See footnote of Table 4.

Table 13. Effect of liming on soil pH, Plant growth, root rot and pea yield in a heavily root rot infested plot with or without green manuring with corn

Lime (tonnes/ha)	Soil pH (8 mo after liming)	Fresh wt of plant (g/10 plants)[1]		Green pea yield (g/10 plants)[1]		Root rot severity (0-9 scale)[2]	
		Green manured	Non-green manured	Green manured	Non-green manured	Green manured	Non-green manured
0	5.5	59a[3](a)[4]	54a(a)	24a(b)	20a(a)	7.3c(a)	7.1c(a)
0.5	5.7	71b(b)	56ab(a)	32b(b)	22a(a)	6.9bc(a)	6.8bc(a)
1.0	5.9	81b(b)	59b(a)	36bc(b)	25b(a)	6.5b(a)	6.9bc(b)
2.0	6.5	103c(b)	65b(a)	48d(b)	28bc(a)	5.1a(a)	5.8a(b)
3.0	7.0	97c(b)	53a(a)	42c(b)	19a(a)	6.2b(a)	6.6b(b)
4.0	7.2	95c(b)	50a(a)	38c(b)	19a(a)	7.3c(a)	78.6d(b)

1) Data were taken in the third week of June, approximately 8 months after liming.
2) Disease severity based on a 0-9 scale, see footnote of Table 3.
3) See footnote of Table 4.
4) (a)-(b) Means are compared between green manured and non-green manured soils. The figures which bear the same letter are not significantly different (P>0.05) according to Student's t test.

In non-green manured soils, an increase in soil pH from 5.5 to 7.0 resulted in a gradual increase in soil bacterial population but there was a slight decrease between soil pH 7.0 to 7.2. On the other hand, populations of both saprophytic and root rot fungi decreased gradually as soil pH increased from 5.5 to 7.2. The population of saprophytic fungi appeared to decrease more quickly than those of root rot fungi.

In green manured soil, an increase in soil pH from 5.5 to 7.2 drastically increased the bacterial popultaion in the soil by approximately 20-fold. The population of both saprophytic and root rot fungi decreased with higher soil pH except for an increase was observed between pH 5.5 and 5.7 for saprophytic fungi. The decrease in fungal population occurred more sharply for root rot fungi than saprophytic fungi.

Comparisons of microbial population in limed soil with or without green manure showed that the soil bacterial population drastically increased and fungal populations (both saprophytic and root rot) decreased in the green manured and limed soil. The decrease was greater for root rot fungi than saprophytic fungi in green manured soil. In non-green manured soil, however, the decrease was greater for saprophytic fungi than root rot fungi (Table 14).

iii) *Effect of different types of green manure on soil microbial activity in a heavily root rot infested soil at pH 6.5 in the greenhouse*

The results (Table 15) showed that microbial population in the soil varied with the type of green manure used. The types of green manure that induced a large increase in soil bacteria tended to result in low root rot severity in peas. Green manure of the grass family (such as rye, sorghum, oats, corn and sudan grass) increased bacterial pupulation more than peas and beans used as green manure. The bacterial population after green

manuring with plants of the grass family were predominantly *Bacillus* spp. and fluorescent *Pseudomonas* spp. Althoug peas and beans also increased soil bacterial population, their increases were small compared with rye, sorghum, oats, corn and sudan grass. Moreover, the small increases in bacterial population by peas and beans were overshadowed by the increase in the population of root rot fungi which reesulted in increased root rot severity (Table 15).

Although liming of acidic soil reduced

Table 14. Effect of liming on soil pH and soil microbial activity in a heavily root rot infested plot with or without green manuring with corn

Lime (tonnes/ha)	Soil pH (8 mo after liming)	Microbial Population[1)] Non-green manured soil: Bacteria (10^5/cm^{3}soil)	Non-green manured soil: Saprophytic fungi (10^3/cm^{3}soil)	Non-green manured soil: Root rot fungi (10^3/cm^{3}soil)	Green manured soil: Bacteria (10^5/cm^{3}soil)	Green manured soil: Saprophytic fungi (10^3/cm^{3}soil)	Green manured soil: Root rot fungi (10^3/cm^{3}soil)
0	5.5	0.6a[2)](a)[3)]	2.3c(b)	2.7de(b)	1.7a(b)	2.1c(a)	2.2d(a)
0.5	5.7	0.9b(a)	2.2c(a)	2.4d(b)	3.1b(b)	2.6d(b)	1.8c(a)
1.0	5.9	2.0c(a)	2.1c(a)	1.9c(b)	10.4c(b)	2.4d(b)	1.4b(a)
2.0	6.5	4.2e(a)	1.0b(a)	1.5b(b)	36.2d(b)	1.6b(b)	0.8a(a)
3.0	7.0	4.4e(a)	0.7a(a)	1.5b(b)	35.4d(b)	1.2a(b)	0.6a(a)
4.0	7.2	3.5d(a)	0.8a(a)	1.2a(b)	34.6d(b)	1.3a(b)	0.6a(a)

1) Samples were taken 8 months after liming.

2) a-d See footnote of Table 4.

3) (a-b) Means within line of respective items (e.g. Bacteria vs. bacteria of non-green manured and green manured) followed by the same letter are not significantly different ($P>0.05$) according to Student's t test.

Table 15. Effect of different types of green manure on soil microbial activity in a heavily root rot infested soil at pH 6.5

Type of green manure	Ave. severity of root rot (0-9)[1)]	Microbal population: Bacteria (10^5/cm^3 soil)	Microbal population: Saprophytic fungi (10^3/cm^3 soil)	Microbal population: Root rot fungi (10^3/cm^3 soil)
Control	7.2	10.7 a[2)]	1.8 a	2.9 d
Pea	8.6	20.0 c	11.7 e	11.2 f
Bean	7.4	16.2 b	8.2 d	5.3 e
Rye	6.5	27.2 d	3.5 c	2.6 d
Sorghum	5.3	44.3 f	3.1 b	1.9 bc
Oats	4.8	64.2 g	3.0 b	1.1 a
Corn	5.5	42.2 f	3.2 bc	1.6 b
Sudangrass	5.4	38.0 e	2.8 b	1.8 bc

1) For 0-9 scale, see footnote of Table 3.

2) See footnote of Table 4.

root rot severity somewhat, the reduction was substantially enhanced with addition of green manure and crop residue of a species unrelated to the crop. Apparently crop residues increased saprophytic bacterial and fungal population which in turn increased soil organic matter. Tu[25] reported an organic matter content of 4% in soil (pH 5.5) which had been planted to peas for 3 consecutive years without interseason green manure. After 3 years of interseason green manure between July 15 to October 30 of each year an overall increase of 1% in soil organic matter was realized without liming of the soil. Experimental results would suggest that, with liming, organic matter in the soil will be increased further as a result of microbial activity.

The present results are consistent with other works[11,13,29] who showed that liming of acidic soils reduced the impact of Fusarium wilt and root rot. Garrett[14] showed that vascular wilts and cortical root rots caused by *formae speciales* of *F. oxysporum, F. roseum, F. nivale,* and *F. solani* are more severe in acidic soils. Cook and Baker[13] and Woltz and Jones[29] postulated that liming of acidic soil caused a reduction in micronutrients sufficient to restrict growth of the pathogen but not the plant.

In addition to liming, several researchers have used plant residues to control root rots. Papavizas[18] reported several situations in which biological control of a pathogen by plant tissues was related to reduction of the inoculum density of the pathogen. Addition of oat straw, corn stover, of alfalfa hay to *Thielaviopsis basicola*-infested soil caused a population reduction of about 90% and almost colmplete elimination of the root rot of bean caused by the pathogen. The population reduction was attributed to the stimulation of germination of endoconidia and chlamydospores of *T. basicola,* with subsequent germling lysis occurring before formation of secondary endoconidia or chlamydospores[1,18,19].

Lewis and Papavizas[17] observed in a greenhouse study that of the 10 kinds of plant tissues incorporated into soil, 9 significantly reduced bean root rot caused by *F. solani* f. sp. *phaseoli.* Mature plant residues were generally more effective than immature ones in reducing root rot. They believed that pathogen survival and destruction are intimately associated with the decomposition of a particular residue that appears to involve volatile and toxicant production, fungistasis, lysis, antagonism and antibiosis.

The present results show that combining liming and green manuring can enhance soil microbial activity. The high level of saprophytic bacterial and fungal activity indicates that antagonism and antibiosis may play an important role in the control of root rot disease. It must be emphasized that combination of liming and green manuring is superior to liming or green manuring alone.

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摘　要

杜瑞章 1991 豌豆根腐病（複合感染）之病因學、生物學及防治　植保會刊 33:17-35.（加拿大農部 Harrow 試驗所）

在渥汰華西南方豌豆根腐病之平均田間發病率爲 26%。複合感染引起的根腐病嚴重影響豌豆的產量。爲了解此病害之病因學，總共從 33 個豌豆田收集 465 個病害標本，進行 782 次的分離試驗，結果獲得 *Fusarium solani* f. sp. *pisi, F. oxysporum* f. sp. *pisi, Aphanomyces euteiches* and *Pythium* spp. 等病原菌，其比例爲 7:4:1:1。*F. oxysporum* 菌株中，race 1 及 race 2 的比例爲 7:4。*F. solani* 對寄主品種間較無選擇性，故未鑑定其生理小種。由 *F. solani*（根腐），*F. oxysporum*（萎凋），*Pythium* 及 *Aphanomyces* 引起的平均發病度（0～9 級的範圍）分別爲 3.2, 8.7, 2.6 及 4.0。通常，感染 *F. oxysporum* 之罹病株終將死亡，而罹患 *F. solani* 者僅表現不同程度之矮化與黃化病徵。另外 *Pythium* 及 *Aphanomyces* 僅少數發生。據此，發展一套病害損失指數（disease damage index, DDI）對上述四種病原菌之相對重要性加以分級。根腐病之 DDI 即是總發病率（26.5%）×病原出現率×病原引起之發病度。結果上述四種病原，*F. solani*，*F. oxysporum*，*Pythium* spp. 及 *A. euteiches* 之 DDI 依序分別爲 45、71、5 及 8。因此，*F. oxysporum* 最重要，*F. solani* 次之，而 *Pythium* 及 *Aphanomyces* 較不重要。基於對豌豆根腐病之病因學及生物學之研究，發展出一套綜合防治方法，包括 (a) 選用種子處理藥劑之新配方，(b) 種植田間抗病品種，(c) 處理適當的殺草劑配方，(d) 應用田間土壤指數的預測方法，(e) 改善耕犁方式，(f) 栽植適當的綠肥作物及 (g) 調節土壤 pH 值。本方法於 1984～1986 年之田間試驗表現能夠控制根腐病，並增產 150%。